Statistical excess of foreground galaxies around high−z radiogalaxies[*]

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Abstract. K−band imaging of a sample of 21 radiogalaxies with $z \sim 1.5$ reveals the existence of a statistical association of foreground galaxies with the positions of the radiosources. The excess is detected within a 1' radius at a high significance level ($> 99.8\%$). K-band light is a good tracer of stellar mass, so this result indicates the existence of an association between foreground mass perturbations and background radiosources, as expected from the magnification bias effect, and confirms previous results obtained for other high−z radio-loud AGN.

Key words: radiogalaxies– gravitational lensing– magnification bias

1. Introduction

The study of statistical associations between foreground galaxies and background AGNs has a long and controversial history. Gravitational lensing seems to provide the best explanation for this phenomenon (see Schneider et al 1992, Narayan and Bartelmann 1996, Schneider 1996 for recent reviews of both theoretical and observational aspects).

The density of a population of flux-limited background sources (e.g. AGNs), magnified by a factor μ by a mass perturbation is changed in two ways. As the angular dimensions of the lensed zone are expanded by a factor μ, the physical size of a region observed through a fixed angular aperture will be smaller than in the absence of the lens. This causes a decrease in the AGN surface density equal to μ^{-1}. On the other hand, the lens will magnify faint sources (which would not have been detected otherwise) into the sample and increase the number of detected AGN. If the slope of the AGN number-counts cumulative

distribution is steep enough, the latter effect would dominate over the former and there would be a net excess of AGN behind the lens. The value of the density enhancement q of these sources around foreground galaxies would be $q = \mu^{\alpha_e - 1}$, where α_e is the effective slope of the background source cumulative number counts (Borgeest et al. 1991).

Observations show that there seems to be positive correlations between foreground galaxies and high−z radio-loud quasar samples (Hintzen et al. 1991, Bartelmann & Schneider 1994, Benítez & Martínez-González 1995, etc.), or heterogeneous samples which contain a considerable fraction of radio-loud quasars (Tyson 1986, Thomas et al. 1995). The results for radio-quiet QSOs are confuse and often even contradictory. Although at small scales there are both positive and negative results (see Narayan 1992), at large scales there are no detections of radio-quiet QSO-foreground galaxy positive correlations but evidences of anticorrelations (Boyle et al. 1988, Benítez & Martínez-González 1997).

This last fact cannot be explained in terms of gravitational lensing alone: although stronger correlations are predicted for radio-loud samples due to the existence of a double magnification bias effect (Borgeest et al. 1991), the correlations should also be observed for radio-quiet QSO samples. These results, however, may be understood if we consider small amounts of dust associated with the lensing masses (Benítez & Martínez-González 1997), a phenomenon which may be called 'dirty' or 'dusty' lensing. In that case, and taking into account the double magnification bias, for a radio-loud sample the density enhancement q_r would be $q_r = \mu^{\alpha_r + \alpha_o - 1} e^{-\alpha_o \tau}$, whereas for the radio-quiet sample $q_o = \mu^{\alpha_o - 1} e^{-\alpha_o \tau}$, where α_o and α_r are respectively the cumulative number-counts slope in the optical ($N(< m) \propto 10^{0.4\alpha_o m}$) and the radio bands ($N(> S) \propto S^{-\alpha_r}$) respectively and τ is the optical depth by dust present in the lensing matter. We have assumed that the absorption is much larger in the optical than in radio, and that the radio flux is approximately independent from the optical magnitude. Then, if e.g. $\mu e^{-\tau} \approx 1$,

we have that $q_r \approx \mu^{\alpha_r - 1}$, independently of the number-counts slope in the optical α_o, and $q_o \approx \mu^{-1}$ for the radio-quiet QSOs.

It is thus specially interesting to determine if the associations with foreground galaxies also occur for other radio-loud AGN samples which have very different optical properties from the quasars, as the radiogalaxies. In Benítez et al. 1995 (B95), an excess of apparently foreground galaxies was found around a sample of 5 radiogalaxies with $1 < z < 2$. In this paper we extend our study to a larger sample (21 radiogalaxies), and perform it in the K band. This band is a good tracer of old stellar populations and makes easier the identification of foreground mass concentrations.

This paper is structured as follows: In Sec. 2 we report the observation and data reduction procedures. In Sec. 3 we describe the results and the statistics. Sec. 4 discusses our main results and conclusions.

2. Observations and data reduction

Our preliminary sample was formed by all the radiogalaxies from the 3C catalogue with $0.95 < z < 2$. We observed 17 sources[1] from this catalogue picking them in function of the availability of their coordinates and completed the final sample with four radiogalaxies with similar characteristics obtained from the literature: 0956+475, 1129+35, 1141+354 and 1230+349. As far as we know there is no bias whatsoever towards the presence of low redshift objects around our sample.

The observations were carried out at the CAHA 2.2m Telescope at Calar Alto with the camera MAGIC on the nights of 1995 January 16-19 and May 16-17. MAGIC uses a 256×256 NICMOS3 HgCdTe detector array. For the purposes of our investigation it is essential to have a wide field in order to determine accurately the background density, so we used the configuration which provided the largest pixel scale, 1.61 arcsec/pixel, which gives a $\approx 6.9 \times 6.9$ arcmin^2 field.

We typically took 27 exposures of 60 sec. for each field. The telescope was nodded among nine positions forming a 20 arcsec square grid. Both in the january and may runs the weather ranged from bad to awful, and some of the exposures had to be rejected due to clouds. The images have been reduced in the standard way for near IR observations. A first pass reduction involved forming a flat field for each frame by median combining the closest frames with a sigma-clipping algorithm. After identifying the most extended and saturated objects, we eliminated them from the raw frames and repeated the procedure. The final, averaged K images were trimmed and only contain the intersection zone which was observed in all the exposures. The median p.s.f. was ≈ 2.5 arcsec. Although the

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[1]   3C013, 3C065, 3C068, 3C124, 3C173, 3C184, 3C194, 3C208, 3C210, 3C256, 3C267, 3C280, 3C294, 3C322, 3C324, 3C326, 3C356

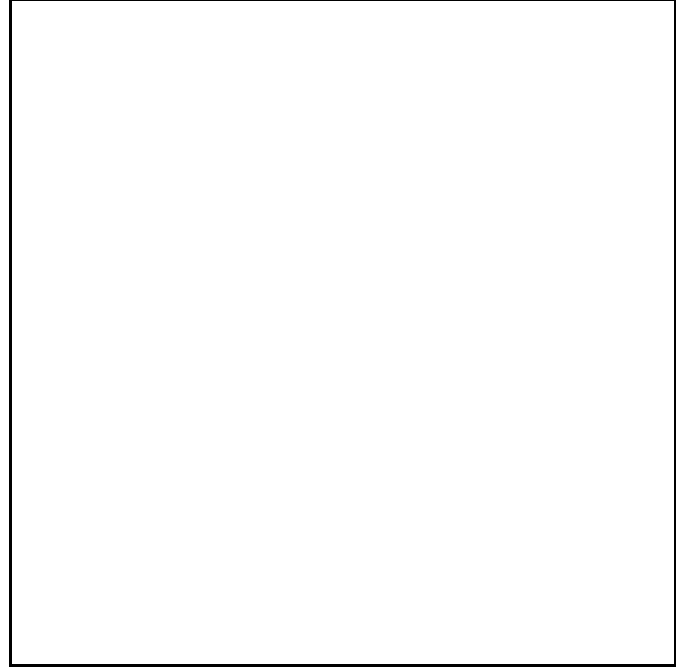nights were not photometric, the way in which the analysis has been performed ensures that our main results are insensitive to photometric uncertainties.

The package SEXtractor (Bertin and Arnouts 1996) was used for image detection and classification. We accurately determined the p.s.f. of each field running the routine SEXseeing several times until it converged to a stable value and then performed the detection after smoothing the frame with a gaussian close to the p.s.f. value.

The star-galaxy classification algorithm correctly identifies the brightest, saturated stars. At fainter magnitudes, with our pixel scale it is virtually impossible to distinguish between stars and galaxies. In any case, any star entering our sample would just tend to dilute any possible excess and lower the significance of our results. So we form our galaxy sample by taking all the objects to which SEXtractor assigns a stellar index smaller than 0.9, which excludes the more conspicuous bright stars. We have checked that the final results are insensitive to variations in the stellar index threshold. We set the completeness limit at the magnitude at which the detected galaxies typically have a photometric error of 0.3. This usually corresponds to $K \approx 18 - 18.5$.

The radiogalaxy has been detected in 11 of the fields, but there are several instances in which either it is fainter than the completion limit (5) or the presence of a bright object close to its position makes impossible either identification or photometry (5). When needed we have established its location in the frame with an accuracy of ≈ 2 arcsec with the help of reference charts from the Digital Sky Survey, and obtained its magnitude from the literature or estimated it with the $K-z$ relationship (McCarthy 1993 and references therein)

The distribution of 'truncated' or incomplete objects in the fields shows that there is a 10 pixel wide zone where SEXtractor loses bright objects because they are too close to the border of the detector. We have excluded this region from our catalogues and also a 10 pixel radius circle around the radiogalaxy to avoid merged objects. The 'useful' surface thus defined contains 1944 galaxies and covers a surface of 645.4 arcmin ^{2}.

3. Statistical analysis and results

To check for the presence of associations due to the magnification bias effect, we have to select a foreground galaxy catalogue and try to avoid the inclusion of any galaxies clustering with the radiogalaxy at its same redshift. We can make use of the fact that the high$-z$ 3C radiogalaxies are representative of some of the brightest known early type galaxies, so they are very likely to be more luminous than any other object at the same redshift, and redder than almost any foreground galaxy. Therefore, any object which is significantly brighter in K than the radiogalaxy is almost certainly in the foreground.

Table 1. Number of objects in the central 1' region

$K - K_{rg}$	n_f	n_e
< -5.0	0	0.09
< -4.5	0	0.19
< -4.0	1	0.28
< -3.5	2	0.75
< -3.0	7	2.16
< -2.5	13	5.63
< -2.0	22	11.04
< -1.5	31	19.02
< -1.0	55	34.34
< -0.5	72	55.91
< 0.0	111	90.48
< 0.5	138	117.98
< 1.0	165	144.38
< 1.5	190	170.88
< 2.0	205	183.48
< 2.5	207	187.69

Fig. 1. Distribution of galaxies as a function of $K - K_{rg}$

We employ a statistical method similar to the one discussed and applied in B95. The number of galaxies found in a central region around the radiogalaxies n_f is compared with the expectation n_e determined from the average density on the whole 'superfield' (including the central region). To compare with previous results for radiogalaxies (B95), a 1' radius circle was chosen. In Fig. 1 we have plotted histograms for n_f (continuous line) and n_e (dashed line) binned in 0.5 mag intervals of $K - K_{rg}$, the difference between each galaxy magnitude and the magnitude of the radiogalaxy in its field. An excess of galaxies is clearly seen in the magnitude bins which are brighter than the radiogalaxies. In Table 1 we have listed n_f and n_e for galaxies brighter than a given threshold in $K - K_{rg}$. In order to have enough galaxies for our statistical analysis we take the objects which have $K < K_{rg} - 1$, which is enough to ensure that the objects are brighter than the radiogalaxies. We find 55 galaxies within the central 1' region which are at least 1 mag brighter than the corresponding radiogalaxy, against an expectation of 34.34 ($q = 1.60$). The density enhancement would be even stronger if we set a brighter threshold ($q = 1.99$ for $K < K_{rg} - 2$; $q = 3.24$ for $K < K_{rg} - 3$) but the significance levels would be lower due to the smaller total number of galaxies in the samples.

How significant is this result? If we placed N_i points at random within a field of surface Ω_{Ti}, the number of points n_i found within a central region of fixed surface Ω_C would be binomially distributed with average $< n_i > = N_i p_i$ and variance $\sigma n_{ri}^2 = N_i p_i (1 - p_i)$, where $p_i = \Omega_C / \Omega_{Ti}$. In our case $p_i \approx 0.1$, which gives a 5% difference with respect to Poisson that would vanish in the limit when Ω_C is much smaller than Ω_{Ti}.

If the results of 21 different independent fields were added up together, the resulting distribution would be approximately gaussian with an average $< n > = \sum N_i p_i$ and a variance $\sigma_r^2 = \sum N_i p_i (1 - p_i)$. We expect that the variance for a real galaxy field σ_{gi}^2 will be larger than that of a random distribution σ_{ri}^2 because of galaxy clustering (Peebles 1980):

$$\sigma_{gi}^2 \approx N_i p_i (1 - p_i) + \frac{(N_i p_i)^2}{\Omega_C^2} \int_{\Omega_C} w_i(\theta_{12}) d\Omega_1 d\Omega_2 \qquad (1)$$

Baugh et al. 1996 have measured an amplitude $A_{15} \approx 0.03$ for the correlation function $w(\theta) = A\theta^{-0.8}$ of $K < 15$ galaxies. As it is well known, the correlation function approximately scales with depth as $w(\theta) = D^{-1}w(\theta D)$, where $D = 10^{0.2(m-M^*)-5}$Mpc (Peebles, 1980). Thus the amplitude will change with the limiting magnitude as $A_K \approx A_{15}10^{0.36(15-K)}$. After calculating the integral of the correlation function with a Monte Carlo taking into account the shape of our region we found that the total dispersion combining the 21 separate fields would be:

$$\sigma_g^2 \approx \sum N_i p_i (1 - p_i) + 35.15 \sum A_i N_i^2 p_i^2 \qquad (2)$$

where A_i is the amplitude of the correlation function corresponding to each field. Thus the 'expected' variance in the number of galaxies within the central region should be $\sigma_g^2 \approx 31.02 + 18.55$. If we measure empirically the rms from our data we obtain a lower value, $\sigma \approx 5.6$, very close to the expectation for a random galaxy distribution. However, this empirical estimation is rather uncertain, because our total surface is only ≈ 10 times larger than the central region, and thus the amount of independent data is very limited. For this reason, we take as a conservative estimate

of the true dispersion the theoretical upper limit, $\sigma_g \approx 7$, which yields a significance of at least 2.95σ, equivalent to a 99.8% significance level.

Incidentally, if we consider the four fields which are common to our sample and to B95, namely 0956+475, 3C256, 3C294 and 3C324 (1217+36 was excluded from the present sample because it was found to be stellar-like in B95), we found 12 foreground galaxies in the central region against an expectation of 7.26, a $q = 1.65$ excess close to the obtained for the full sample.

To further check the above mentioned results, we have measured the central density of objects which are *fainter* than our foreground sample. The sample thus defined contains 1587 galaxies. No excess is detected: there are 152 galaxies in the central box against an expectation of 153.3.

4. Discussion and conclusions

There are few deliberate searches for magnification bias effects around high$-z$ radiogalaxies in the literature. Besides, the comparison of our results with other works is complicated by the fact that as far as we know, this is the first such analysis done in the near IR.

Our present result clearly confirms the excess found in B95. However, a bootstrap analysis shows that subsamples of 4 fields chosen randomly from our sample yield overdensities ranging from $1.14 < q < 2.09$ (68% confidence limits). If the average density enhancement q were slightly lower, which could be the case for other galaxy or AGN samples, values of $q \approx 1$ could have been obtained in a non-negligible number of cases. This should be taken into account when working with very small samples, as in Fried 1996.

Hammer and Le Fevre (1990) claim that there are nine times more high$-z$ 3CR galaxies within five arcsec of $R \leq 21$ galaxies than expected from a random distribution. Although we cannot check the excess at those scales because of our pixel scale, our results confirm that samples as the 3CR radio sources may be considerably affected by gravitational lensing.

In a recent paper, Roettgering et al. (1996) do not find any excess of bright galaxies $R < 21.5$ around a sample of 11 ultra-steep-spectrum radio galaxies with $z > 1.8$. However, the scale of their field is smaller than ours, $r < 100''$. The number of foreground galaxies found within $100''$ of our radiogalaxies is 129. Thus, the expectation within the central $60''$ would be 44.27 ± 7.9 (the rms has been estimated as above). We found 55, that is a $q = 1.24 \pm 0.18$ overdensity with a 1.35σ significance level. For a sample of 11 galaxies the significance would have been just $\approx 1\sigma$, against the almost 3σ that we obtain in our larger fields. In any case, this comparison is not very conclusive, as far as neither the filter, nor the radiogalaxy type or redshift distribution are the same.

We have determined the existence of an statistical excess of foreground galaxies around a sample of background, high redshift radiosources. The way in which the foreground sample galaxies have been selected almost excludes the possibility of their being physically associated with the radiogalaxies. The only consistent explanation — at least qualitatively—for this fact is the magnification bias caused by gravitational lensing by the dark matter perturbations traced by the foreground objects.

The small size of the sample precludes a detailed, quantitative study of the form of the radiogalaxy-galaxy correlation function. It would be therefore desirable to use larger, well understood radiogalaxy samples with accurately defined properties to obtain a robust estimate of q which could be compared with theoretical estimations.

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